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Camp Century was a military base constructed by the US Army Corps of Engineers in 1959 in the near-surface layers of the Greenland ice sheet at 77.13°N, 61.03°W and 1886 m above sea level (Clark 1965; Fig. 1). The base housed up to 200 military personel and was continuously occupied until 1964. After three years of additional seasonal operation, the base was abandoned with minimal decommissioning in 1967. Recent Danish scholarship has documented the political and military history of Camp Century in detail (Nielsen & Nielsen 2016).

In 2016, the Geological Survey of Denmark and Greenland (GEUS) participated in a multi-nation study that presented regional climate simulations that suggested the ice-sheet surface mass balance at Camp Century may change from net accumulation to net ablation by 2100 under the UN Intergovernmental Panel on Climate Change RCP8.5 'business-as-usual' climate scenario. However, according to Colgan *et al.* (2016), net accumulation would persist beyond 2100 at Camp Century under the climate-change mitigation characterised by RCP4.5, an approximately 'Paris Agreement' climate scenario.

In 2017, in response to concerns from the Government of Greenland over the potential to remobilisation of contaminants from Camp Century within the next century, the Government of Denmark established a programme for long-term climate monitoring and detailed one-time surveying of the debris field at Camp Century (Colgan *et al.* 2017). This report describes the initial field activities of the Camp Century Climate Monitoring Programme in the context of the four programme goals:

1. To continuously monitor relevant climate variables, including the depth to which meltwater percolates, at the Camp Century site.
2. To regularly update annual likelihoods of meltwater interacting with abandoned materials at the Camp Century site over the next century.
3. To map the estimated spatial extent and vertical depth of abandoned wastes across the Camp Century site.
4. To publicly report all findings from the Camp Century Climate Monitoring Programme in a timely manner.

Field logistics

Field activities of the Camp Century Climate Monitoring Programme were initiated in summer 2017, when a six-person team spent two weeks at the Camp Century site (19 July to 3 August). There is no abandoned infrastructure visible at the ice-sheet surface at Camp Century (Fig. 2). Debris field location, as well as zones of restricted drilling depth, were estimated prior to field work (Fig. 3). This was done by georeferencing a historical site map using a single tie-point, the location of the original drill tower, corrected for motion since its last precise survey in 1986 (Gundestrup *et al.* 1987). The 2017 summer camp, which consisted of three common

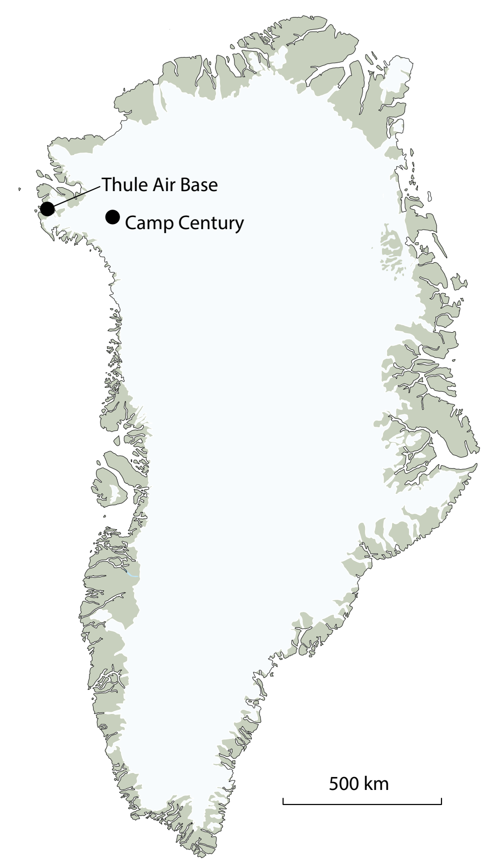

Fig. 1. Location of Camp Century that was constructed by the US Army Corps of Engineers in 1959 in the Greenland ice sheet. Camp Century was abandonned in 1967.

Fig. 2. The temporary ice-sheet camp at 1600 UTC on 20 July 2017. The camp consisted of three common tents and six personal tents. There was persistent cloud cover with frequent storm conditions and a mean wind speed of 8.8 m/s. No abandoned infrastructure is visible at the ice-sheet surface; the entire debris field is now subsurface as a result of net snow accumulation since closure.

tents and six personal tents, was established within the debris field, approximately aligned with the location of post-closure summer camps (Kovacs 1970). Although decamped entirely, the footprint of the 2017 summer camp will likely be visible in subsequent ice-penetrating radar surveys due to the formation of massive wind-sculpted snowdrifts around it.

During field work, there was persistent cloud cover with frequent storm conditions. The mean wind speed was 8.8 m/s, and the maximum 1 hour mean wind speed was 18.3 m/s (Beaufort 8). Thule Air Base, located approximately 200 km west, served as logistical base for the field work. A ski-equipped Twin Otter aircraft was used to transport 3200 kg of equipment and supplies to and from the ice sheet. Field work consisted of installing three automated instrument stations, drilling boreholes for instrument installation and firn sampling, surveying velocity stakes, and collecting ice-penetrating radar profiles. Of the 175 m firn core drilled, 135 m were analysed in the field and 40 m were transported to Copenhagen for more detailed radionuclide analysis by the Center for Nuclear Technologies at the Technical University of Denmark.

Instruments and data

Climate measurements were initiated using automated weather station technology previously developed by GEUS. The automatic weather station design has a proven record of more than 175 station-years of deployment in Greenland since its introduction in 2007 (Citterio *et al.* 2015). The primary weather station at Camp Century (CEN) measures air temperature and humidity, wind speed and direction, atmospheric pressure, upward and downward shortwave and longwave radiation, subsurface (snow/ice) temperatures to 10 m

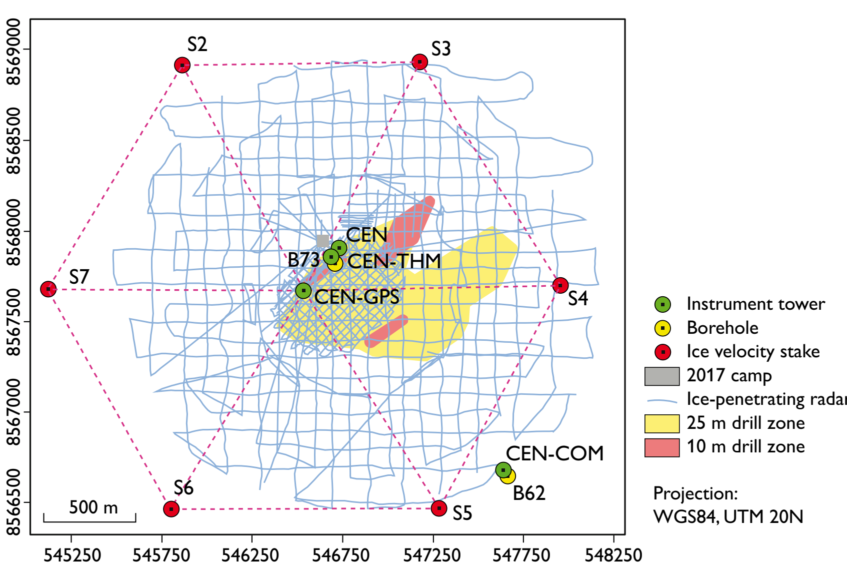

Fig. 3. Overview of initial field activities at Camp Century. Recently constructed instrument towers refer to the primary weather station ('**CEN**'), the supplementary thermistor station (**CEN-THM**), the supplementary compaction station (**CEN-COM**) and the supplementary global positioning system station (**CEN-GPS**; to be installed). Boreholes refer to the 73 (**B73**) and 62 (**B62**) m firn cores. Restricted drill zone depths were assessed based on georeferencing of a historical as-built site map (Kovacs 1970).

depth, and snow depth, as well as diagnostic parameters such as battery voltage. The temperature of the relatively porous near-surface ice-sheet layer known as firn is also measured by a supplementary thermistor station (CEN-THM) to a depth of 73 m, which approximates local pore close-off depth (Fig. 3).

Ice-sheet structure was analysed with 73 and 62 m deep firn cores, hereafter referred to as B73 and B62. Firn density and melt percentage were measured to a minimum depth of 62 m at locations inside and outside the debris field (Fig. 4). A third automatic station was deployed to measure the compaction rate of snow into ice, or vertical strain, over the 0 to 5 m, 0 to 20 m and 1 to 62 m depth ranges. This third automatic station, the supplementary compaction station (CEN-COM), is located outside the debris field. All three automatic stations satellite-transmit their measurements in near-real-time to *www.campcenturyclimate.dk*. A fourth station that records observations from the global positioning system (CEN-GPS) will be installed to continuously monitor ice flow. These climate and ice data will be used to calibrate and validate future simulations of firn evolution.

Preliminary interpretation

The measurements from the automated weather station (CEN) record that midday air temperature exceeded 0°C for three days during the operational period of the 2017 summer camp. The maximum one-hour mean air temperature was 1.8°C. Under these warm conditions, surface melt quickly froze to moving drill parts when the drill was lowered into cold winter firn. This necessitated a two-day suspension of drilling. Preliminary analysis of the B73 deep thermistor measurements, located within the debris field, indicates that the annual temperature cycle in near-surface snow and ice temperatures penetrates to *c.* 12 m depth (Fig. 4). Beyond this depth, year-round firn temperatures appear to remain *c.* −24°C. In summer 2017, there was limited meltwater production and refreezing, with no apparent change in firn temperature beyond this annual diffusion cycle.

Preliminary analysis of near-surface firn structure indicates that refrozen meltwater layers are readily identifiable in the uppermost 15 m of the firn. The largest of these layers is *c.* 8 cm thick, which represents the melt-and-refreeze of *c.* 25% of annual snowfall (Buchardt *et al.* 2012). The firn cores suggest that meltwater movement beyond the annual layer is unlikely. Near-surface firn densities are similar both inside and outside the debris field to 32 m depth (Fig. 4). Between 32 and 35 m depth, firn density is significantly greater within the debris field. This high-density layer is slightly discoloured in appearance and likely reflects enhanced compaction and pollution during the *c.* 1960–1964 active period. Below this active layer, firn densities are similar inside and outside the debris field. After drilling B73 through the high-density active layer, pressurised hydrocarbon vapours vented from the borehole until it was backfilled. Mobile hydrocar-

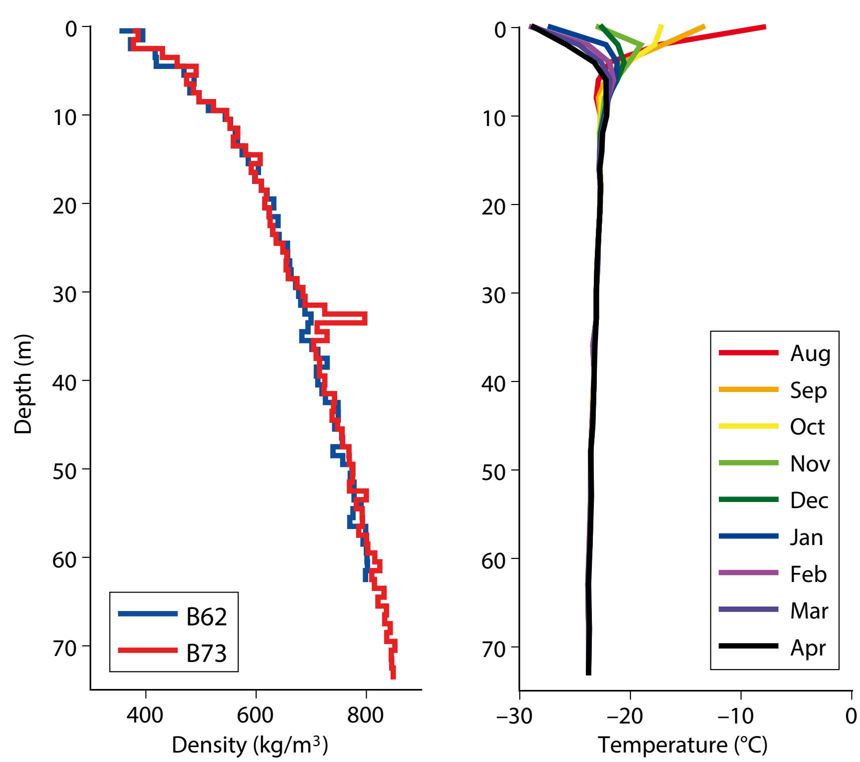

Fig. 4. **Left:** Near-surface firn density profiles measured both inside (**B73**) and outside (**B62**) the debris field. The high-density layer between 32 and 35 m depth within the debris field likely reflects enhanced compaction during the *c.* 1960–1964 active period. **Right:** Near-surface snow/ice temperatures at **B73** inside the debris field. The annual temperature cycle penetrates to *c.* 12 m depth, with year-round firn temperatures remaining *c.* −24°C below this depth.

bon vapours were not anticipated, and vapour-tight equipment was not available on-site to opportunistically sample these vapours.

Radar survey

Data from the one-time summer 2017 radar survey are being analysed to perform a detailed assessment of the horizontal extent and vertical range of the debris field. 100 and 250 MHz ice-penetrating radar data were collected by cross-country skiing in a dense grid pattern over the Camp Century debris field (Fig. 3). The radar profiles, each tagged with global positioning system coordinates, will be available on the programme website. A preliminary field analysis of the ice-penetrating radar data shows that the sub-surface debris field is *c.* 2 km in diameter, with debris ranging between *c.* 20 and 100 m depth. This ice-penetrating radar data will permit improved geo-referencing of historical as-built site maps, via precisely positioning key subsurface infrastructure features, which will facilitate delineating the debris field beyond the extent recorded by as-built site maps.

Programme outlook

This report describes the initial field activities of the Camp Century Climate Monitoring Programme in the context of programme goals. Near-real-time climate and ice measurements from automated stations, ice-penetrating radar profiles, as well as programme outreach materials and publications, can be accessed at *www.campcenturyclimate.dk*. Subsequent field work at Camp Century will be undertaken, as needed, to service deployed instrumentation. During these subsequent site revisits, ice-velocity stakes will be resurveyed to precisely measure the relatively slow (<5 m/yr) ice velocity over several years.

Data analysis, in support of observationally-constrained numerical simulations of the evolution of meltwater and firn, is the major programme focus. While climate change now gives Camp Century previously unanticipated social significance, the sustained effort of the Camp Century Climate Monitoring Programme will continue to provide Danish and Greenlandic stakeholders open access to relevant *in situ* measurements and model projections. Refined knowledge of the spatial extent and vertical range of the debris field, as well as the changes in firn structure and meltwater production anticipated under climate change, will inform science-based discussions of the shifting fate of Camp Century.

Acknowledgements

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